Erodibility of Mud: Characterization and Prediction

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LONG-TERM GOALS

To improve our capabilities for measuring and predicting erosion rates, sediment flux, water clarity and bed strength in muddy coastal environments, particularly with respect to their evolution through time on tidal flats.

OBJECTIVES

The objectives of my work within the Tidal Flats DRI are:

1. Measure temporal variations in erodibility and shear strength of tidal flat and channel sediment in Willapa Bay.
2. Measure temporal variation in consolidation and erodibility of sediment from Willapa Bay under controlled laboratory conditions;
3. Correlate temporal and spatial variations in erodibility with other sediment, channel and flow characteristics.
4. Use the results to improve formulations for mud deposition, consolidation, resuspension and net erosion in coastal sediment transport models.

APPROACH

Laboratory and field measurements of erodibility were made using a Gust erosion chamber. The erosion chamber permits shear stresses from 0.01Pa – 0.40Pa to be applied to the surface of sediment in a core tube and the resulting suspended sediment to be sampled for concentration, grain size and mass eroded. Cores were collected in the field using a hand corer that leaves the sediment-water interface undisturbed. Deposits were created in the lab by slurrying sediment from the field site with salt water and allowing the suspension to settle in a core tube. The field experiments were made in conjunction with a team of investigators who, collectively, also measured porosity, shear strength, grain size, water levels, waves, meteorological conditions, velocity and suspended sediment concentrations and properties, accumulation rates, and depositional characteristics.

The modeling is proceeding on several fronts. I have adapted a 1-dimenionsional, steady-state shelf sediment transport model that includes wave-current interaction and sediment dynamics (cohesive and

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non-cohesive) to directly use the results of the erosion chamber tests to set the bottom boundary condition on sediment in suspension. I have also worked with a post-doc, Ilgar Safak, to develop an implementation of FVCOM, a three-dimensional unstructured grid finite-volume coastal ocean model, to examine sediment dynamics in secondary channels in Willapa Bay. I will be using the laboratory and field erosion measurements to test and improve the characterization of consolidation and resuspension of mud deposits by tidal flows in both models and extend the FVCOM modeling to intertidal systems of varying tidal amplitude (micro- to mega-tidal) with my remaining project funding.

WORK COMPLETED IN FY11

1. Completed processing, QA/QC and compilation of all erosion test data.
2. Correlation analysis of erodibility metrics against sediment and bed characteristics (texture, porosity) and examination of influence of forcing conditions.
3. Submitted a manuscript to Continental Shelf Research describing the main results of the field study of erodibility on the Willapa Bay tidal flats. A presentation was also given at the 2010 Fall AGU Meeting.
4. Implementation and preliminary model calculations using FVCOM of tidal flow and sediment transport in a secondary tidal channel-flat complex like that in Willapa Bay.

RESULTS

I measured erosion rates on tidal flats and in an adjacent secondary channel in southern Willapa Bay, WA, in September 2008, March 2009 and July 2009 and February 2010. Replicate erosion measurements were made at almost all sites by Brent Law. Complimentary measurements included grain size of surface sediment and eroded sediment (Brent Law), porosity (Rob Wheatcroft) and sediment strength (Mark Barry). In addition, Paul Hill and Tim Milligan measured flow and suspended sediment at nearby sites on the flats and in the channel, Andrea Ogston and Dan Nowacki measured flow and suspended sediment at another site in the channel and Chuck Nittrouer and Katie Boldt collected core samples from the flats and channel.

Across and along channel-flat variations in erodibility
Erosion tests were made in February 2010 for samples along a flat-channel-flat transect (T-Transect) across C-Channel, located ~75m from edge of Bear River Channel. Cumulative mass eroded was similar on B-Flat (BF, on north side of channel) and C-Flat (CF, on south side of channel), ranging from 0.005 – 0.034 kg m^{-2} at the maximum bed shear stress of 0.40 Pa. Significantly more sediment, 0.13 kg m^{-2}, was eroded near the channel center. Cumulative mass eroded at on the northern channel flank was similar to that measured in the center of the channel, while erosion on the southern channel flank was similar to the rest of the CF sites.

Erosion measurements in March 2009 were made along a short flat-channel transect, about 25 m closer to Bear River Channel. Average cumulative mass eroded on BF and CF were a little higher than in February 2010, ranging from 0.015 – 0.042 m^{-2} at $\tau_b = 0.40$ Pa. Erosion in the channel was roughly 50% higher than that on the flats, but significantly lower than measured in February 2010 for stresses > 0.16 Pa.

Erosion measurements in July 2009 focused on an along-channel transect. However, several short across-channel transects were also sampled, one that occupied the same sites as the March 2009 measurements and the other included near-channel sites on T-Transect. Cumulative mass eroded on the flats ranged from of 0.004 – 0.048 kg m^{-2} at τ_b = 0.40 Pa, similar to values observed in March 2009 and February 2010, with as much within-flat variability between the two transects as there is between flat and channel within each transect. Differences between average cumulative mass eroded on BF and CF were not significant during any of the sampling periods and data for both flats were combined.

Erosion tests were made in July 2009 for samples on an along-channel transect (C-Transect), extending from close to the mouth of C-Channel to about 350 m up-channel from the edge of Bear River Channel. We attempted to take the cores in the deepest part of the channel, but one sampling site (CC6) was located closer to the channel bank adjacent to BF. Average sediment mass eroded showed no clear trend along the channel. Cumulative mass eroded ranged from 0.01 – 0.04 kg m^{-2} at τ_b = 0.40 Pa except for site CC6, where cumulative mass eroded reached 0.08 kg m^{-2}. A smaller set of along-channel sites was tested for erodibility in February 2010, when cumulative mass eroded in C-Channel ranged from 0.09 – 0.17 kg m^{-2} at τ_b = 0.40 Pa, significantly higher than was observed at all but site CC6 in July 2009.

Seasonal variations in erodibility
Average cumulative mass eroded as a function of shear stress on the tidal flats adjacent to C-Channel was similar during all sampling periods (Table 1), as was cumulative mass eroded on BF and CF during each sampling period. In contrast, channel-bed sediment was much more erodible in February 2010 than in July 2009, excluding Site CC6 (Table 1). The differences were modest (~ factor of 2) but significant at the lower shear stresses, but were much more pronounced (> 5 times) at the higher shear stresses. We made only two measurements of channel-bed erosion in March 2009, but these suggest that the erodibility of this sediment was between that measured in February 2010 and July 2009, and well below the values of cumulative mass eroded at the higher stresses in February 2010. Comparison of two sites on the northern channel flank suggests that sediment comprising that flank remains relatively erodible year round. In contrast, the southern channel flank behaved more like the flats.

The appearance of the tidal flats in the study area changed markedly between our three sampling periods. In March 2009, the coldest and wettest of the sampling periods, the flats were mostly unvegetated and we did not note any widespread microalgae on the sediment surface. In July 2009, the warmest, driest and sunniest sampling period, the flats were generally covered with Z. japonica although the density was sparse enough that some cores contained stems while others did not. In February 2010, the flats had only a few remnant Zostera stems on the surface. There was, however, a visible layer of diatoms on much of the flat surface, giving the flats a rusty-colored tinge. Despite the biological changes we observed on the tidal flats, these results indicate that biological processes were not the dominant control on tidal flat erodibility in our study area.

Quantifying erodibility
An average of 15-23 g m^{-2} of sediment was resuspended from the tidal flat sites sampled in our experiments, equivalent to the uppermost few tenths of a millimeter of the sediment bed. For all stresses that produced resuspension of tidal flat sediment in our erosion tests, the supply of erodible sediment was generally exhausted by the end of the 20-min during which each stress was held constant. The results suggest that resuspension and transport of tidal flat sediment in southern Willapa Bay is supply limited and erodibility is primarily controlled by the rate of increase of critical shear

stress with depth below the bed surface rather than the rate at which sediment can be entrained from the surface.

Average critical shear stress profiles for the flats and channel were quantified using a power-law fit to cumulative mass eroded vs. shear stress (Figure 1). Slopes and intercepts of the power-law fits to average cumulative mass eroded on the flats for the three sampling periods do not differ significantly from the overall average values for the flats. The average power-law relationship for the flats is CME $= 0.126\ \tau_b^{2.03}$, where CME = cumulative mass eroded. Channel-bed erodibility in July 2009 is also well described by this relationship. In March 2009, channel-bed values of cumulative mass eroded were more than 60% larger than in July, but the sample size in March was too small to determine whether these differences were significant. The average power-law relationship for the channel bed in February 2010, the sampling period when it was most erodible, is CME $= 2.83\ \tau_b^{3.30}$; the slope and intercept are significantly greater than we observed for the channel at any other time or for the flats at any time.

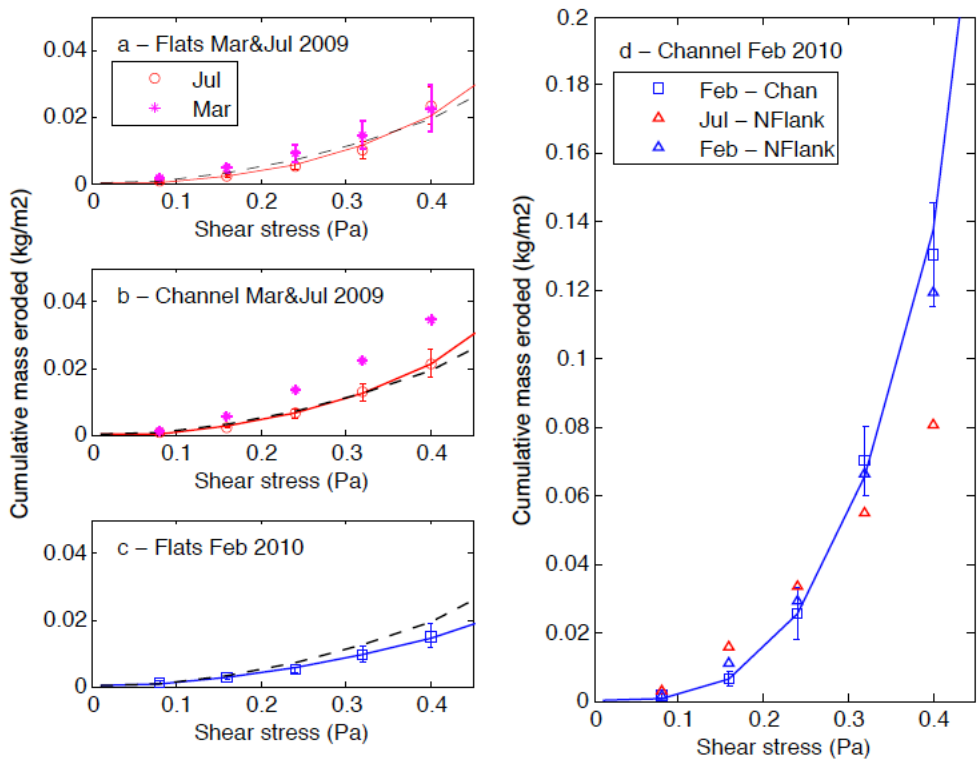

Figure 1. Cumulative mass eroded as a function of bed shear stress. Symbols are averages of cumulative mass eroded for all flat or channel sites at the indicated time; vertical bars show standard error. The curves are power-law fits to the measurements. a) Average for BF and CF and b) average for CC in March and July 2009. c) Average for BF and CF and d) average for CC in February 2010. Triangles in d) show values for the northern flank of CC in July 2009 and February 2010.

Relationship to porosity and grain size metrics
A regression analysis revealed that three parameters, porosity 1-2 mm below the bed surface, porosity 2-4 mm below the bed surface and floc fraction, were significantly correlated with total mass eroded in February 2010 ($p<0.05$). The best correlations for total mass eroded were with porosity 2-4 mm below the surface ($r^2=0.67$) and floc fraction ($r^2=0.78$). Total mass eroded at sampling sites in March and July 2009 was not significantly correlated with any measure of grain size or porosity at those sites. When these are added to the February 2010 values, however, the correlations with porosity 2-4 mm below the surface and with floc fraction remain significant, although values of r^2 become smaller (0.29 and 0.32, respectively). The slopes of power-law fits to cumulative mass eroded vs. bed shear stress for individual sampling sites were not significantly correlated with porosity or grain size metrics for any sampling period.

The slopes and intercepts of the power-law fits were significantly correlated with average porosity (Fig. 2) as was average total mass eroded ($r^2 = 0.85$; not shown). When the results for the 2 cores from the northern channel flank (one in July 2009, the other in February 2010) were added to the regression (* in Fig. 2), the relationships between power-law slopes and intercepts and porosity 2-4 mm below the surface remained significant, while the relationship between total mass eroded and porosity was no longer significant. Thus, porosity just below the sediment surface was the best predictor of erodibility in our study area.

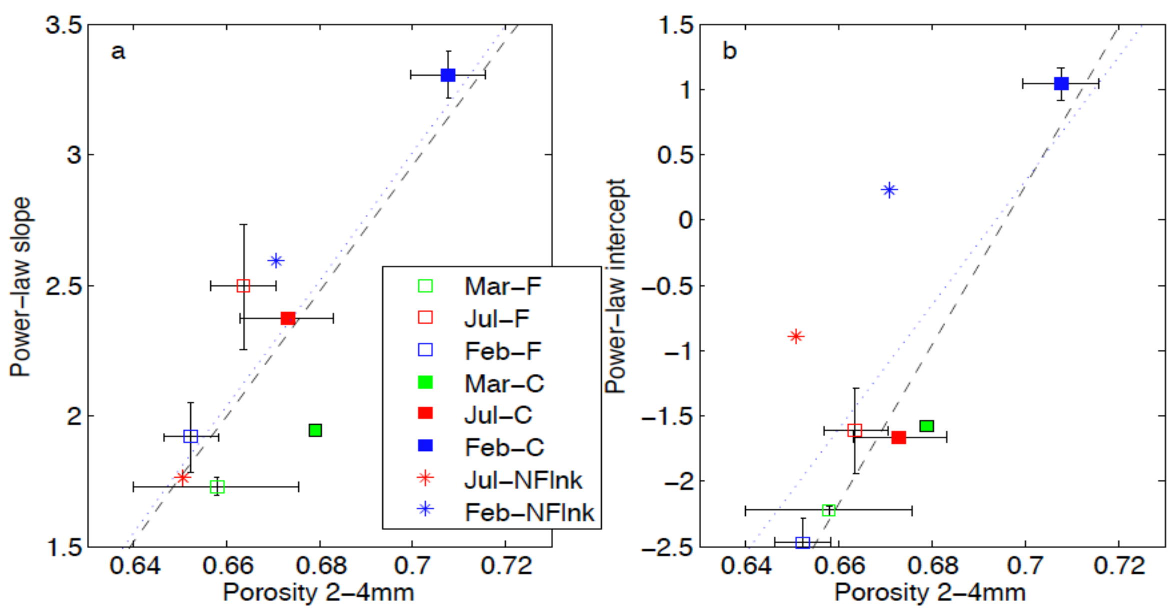

Figure 9. Correlation between average porosity 2-4 mm below the sediment surface (P24) and the a) slopes (PLS) and b) intercepts (PLI) of power-law fits to average cumulative mass eroded vs. bed shear stress (Table 4). Both correlations are significant ($p < 0.05$). The horizontal and vertical bars show standard error for each parameter, with the exception of C-Channel in March 2009 (Mar-C) and the northern channel flank in July 2009 and February 2010 (Jul-NFlnk and Feb-NFlnk) for which values for only one sampling site are available. The regressions equations (dashed lines) for the flat and channels averages are PLS = 23.9*P24 – 13.8 ($r^2 = 0.69$) and PLI – 60.7*P24 – 42.4 ($r^2 = 0.92$). The dotted regression lines, which include the channel flank sites as well, are also significant, with $r^2 = 0.69$ for PLS and $r^2 = 0.52$ for PLI.

Modeling channel-flat sediment suspension and exchange

Post-doc Ilgar Safak has developed an implementation of the three-dimensional, unstructured grid, finite-volume coastal ocean model with a directional spectral surface wave model (FVCOM-SWAVE) for a generalized tidal flat-channel complex based on C-Channel and adjacent flats in Willapa Bay. The model accounts for tidal circulation, wind-generated currents and waves, wave-current interaction, and sediment processes in a unified sense. We are testing FVCOM against field observations of tidal water levels, current velocities and surface waves in C-Channel and adjacent flats (Nowacki and Ogston, submitted; Hill et al, submitted; my water-level and wave measurements). Preliminary model runs have been made for the period 26 Feb – 4 Mar 2010 (Fig. 3). Modeled current speeds and suspended sediment concentrations (SSC) in the channel are qualitatively consistent with observations. Curves of vertically averaged current speed and SSC as a function of water level show peaks just before the flats are drained on ebbing tides and just after they are flooded on flooding tides consistent with observed pulses in current speed and SSC (Nowacki and Ogston, submitted; Hill et al, submitted).

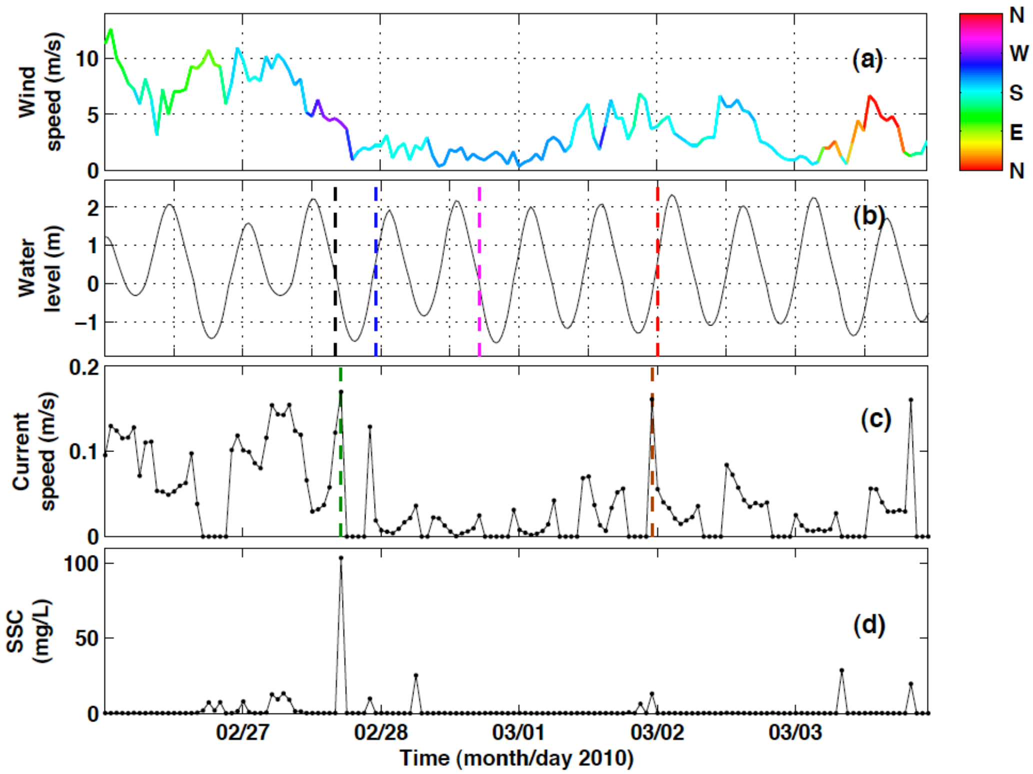

Figure 3: Time evolution of (a) wind speed/direction (Color indicates where the wind is blowing from, i.e., red corresponds to Northerly winds); (b) water level; (c) current speed and (d) suspended sediment concentration at a location near the mouth of the channel

IMPACT/APPLICATION

- Quantification of the role of spatial and seasonal variations in erodibility on tidal flats.
- Better understanding of the role of time-dependent consolidation on tidal-flat sediment erosion.
- Numerical modeling of tidal flat sediment transport and morphologic evolution.

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